



Response of wind erosion dynamics to climate change and human activity in Inner Mongolia, China during 1990 to 2015

Haiyan Zhang^{a,b}, Jiangwen Fan^{a,*}, Wei Cao^a, Warwick Harris^c, Yuzhe Li^a, Wenfeng Chi^{a,d}, Suizi Wang^{a,b}

^a Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

^b University of Chinese Academy of Sciences, Beijing 100049, China

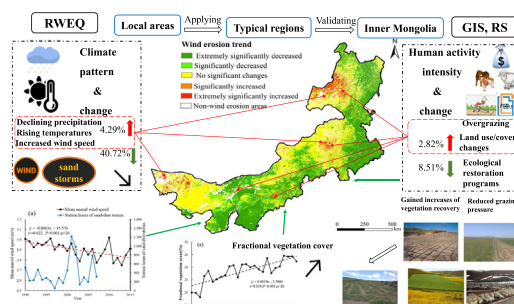
^c Landcare Research, P.O. Box 69040, Lincoln 7640, New Zealand

^d Inner Mongolia Agricultural University, Hohhot 010018, China

HIGHLIGHTS

- The spatial and temporal dynamics of wind erosion in Inner Mongolia from 1990 to 2015 are described.
- Attributions of climate change and human activity to wind erosion changes in Inner Mongolia are distinguished.
- Some targeted management strategies for reducing the hazard of wind erosion are proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil erosion caused by wind is a serious environmental problem that results in land degradation and threatens sustainable development. Accurately evaluating wind erosion dynamics is important for reducing the hazard of wind erosion. Separating the climatic and anthropogenic causes of wind erosion can improve the understanding of its driving mechanisms. Based on meteorological, remote sensing and field observation data, we applied the Revised Wind Erosion Equation (RWEQ) to simulate wind erosion in Inner Mongolia, China from 1990 to 2015. We used the variable control method by input of the average climate conditions to calculate human-induced wind erosion. The difference between natural wind erosion and human-induced wind erosion was determined to assess the effect of climate change on wind erosion. The results showed that the wind erosion modulus had a remarkable decline with a slope of 52.23 t/km²/a from 1990 to 2015. During 26 years, the average wind erosion for Inner Mongolia amounted to 63.32 billion tons. Wind erosion showed an overall significant decline of 49.23% and the partial severe erosion hazard significantly increased by 7.11%. Of the significant regional decline, 40.72% was caused by climate changes, 4.29% was attributed to climate changes and 2.82% to human activities, mainly overgrazing and land use/cover changes. During the study, the driving forces in Inner Mongolia of wind erosion dynamics differed spatially. Timely monitoring based on multi-source data and highlighting the importance of positive human activities by increasing vegetation coverage for deserts, reducing grazing pressure on grasslands, establishing forests as windbreaks and optimizing crop planting rotations of farmlands can all act to reduce and control wind erosion.

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* Corresponding author.

E-mail addresses: zhanghaiyan823@163.com (H. Zhang), fanjw@igsrr.ac.cn (J. Fan).

1. Introduction

Soil loss caused by wind erosion has become a major cause of land degradation and a restriction to sustainable development in arid, semi-arid and even sub-humid regions of North China (Chen et al., 1994; Du et al., 2016). According to the first-ever nationwide water resources survey (2010–2012), the total area affected by wind erosion in China was 165.6 million ha. In particular, it was shown to affect 31.8% of the area of Inner Mongolia (Liu, 2013). Wind erosion significantly decreases soil fertility and plant productivity by blowing stocks of nutrients and organic matter away (Zhao et al., 2017) and also causes air pollution through wind-blown soil particles and chemicals (Du et al., 2016).

The dynamics of wind erosion are driven by both natural processes and human activity. Climate, especially near-surface winds, can strongly affect the process of wind erosion by displacing or removing the topsoil from the land surface (Pi et al., 2017; Tegen et al., 1996). Several human activities can affect wind erosion through changing underlying surface conditions (Zerull and Leh, 2011). Having had severe climate change and high intensity human activity, there has been a widespread increase of soil erosion and its associated risks in China. Several studies have investigated the spatial features, change dynamics, and influencing factors of wind erosion at different scales of space and time (Du et al., 2016; Gong et al., 2014; Jiang et al., 2018a; Shen et al., 2016). However, fewer studies have evaluated the separate contributions of climatic and anthropogenic factors on variations of wind erosion. In particular, previous studies have commonly analyzed the effect of human activity on the negative causes of wind erosion (including land use/cover changes and overgrazing) without adequate consideration of effects such as ecological restoration programs that alleviate wind erosion (Fu et al., 2017). Therefore, separating the wind erosion dynamics induced by climate change and those directly due to human activity, and identifying the major drivers, can provide crucial information for designing measures to reduce wind erosion.

Inner Mongolia has a critical need for ecological protection and defense against sandstorms and wind erosion. Having wide distribution and occurrence of desertification processes, low rainfall and droughts, and frequent strong winds, Inner Mongolia is subjected to frequent occurrence of severe sand and dust storms and has suffered severe soil erosion for a long time (Du et al., 2016; Yue et al., 2015). Additionally, Inner Mongolia is the major source of sandstorms that affect China, Korea and Japan, with Beijing and the neighbouring areas being the locality of greatest concern (Wang et al., 2018). However, wind erosion research in Inner Mongolia has been limited and has mainly focused on soil erosion processes associated with wind. The research that has been done has only involved local areas, simplified indicators, or short time scales (Du et al., 2015). As well, there is a lack of comparative study of wind erosion at large scales. Wind erosion dynamics for the whole of Inner Mongolia has not been comprehensively characterized. Furthermore, the direction and magnitude of climate change and human activity in driving the changes of wind erosion in Inner Mongolia have not been accurately separated. In this study, we endeavor to define an optimal quantitative assessment method to evaluate the relative effects of climate change and human activity on the wind erosion of the region.

Wind erosion assessment has applied various methods from empirical or semi-empirical equations to theoretical equations, and spatial scales from micro-plots to large geographical scales. Among them, the Wind Erosion Prediction System (WEPS) (Hagen, 1991) and the Revised Wind Erosion Equation (RWEQ) (Fryrear et al., 1994) are the most widely used. As study of wind erosion started rather late in China, there is still a lack of basic experimental data and development of process models for the WEPS. The RWEQ model simplifies the complexity of wind erosion but does comprehensively consider the effects of wind speed, precipitation, temperature, soil texture, topography, and vegetation cover on wind erosion (Fu et al., 2017; Van Pelt et al., 2004). After parameter calibration and upscaling, as well as application

in the United States of America (Van Pelt et al., 2004; Zobeck et al., 2003), the RWEQ model has also been successfully used in other parts of the world at large scales, including the Argentinean Pampas (Buschiazzi and Zobeck, 2008), Egypt (Fryrear et al., 2008), some areas in China, e.g. the Beijing-Tianjin Sandstorm Source Region (Jiang et al., 2018b), the watershed of the Ningxia-Inner Mongolia reach of the Yellow River (Du et al., 2017), the Three-River Headwaters Region (Jiang et al., 2016a), Hunshandake Desert (Shen et al., 2016b) and Qinghai Province (Jiang et al., 2015).

Thus, we used the RWEQ model to calculate actual wind erosion and used the model variable control method by input of the average climate conditions to calculate human-induced wind erosion. Climate-induced wind erosion was estimated by considering the difference between natural and human-induced wind erosion. By comparing the trends of climate-induced and human-induced wind erosion over time, we determined whether climatic factors or human activity were determining variation of wind erosion. The objectives of this paper are: (1) to analyze the spatial and temporal changes of wind erosion in Inner Mongolia from 1990 to 2015; (2) to investigate the relative contributions of climate change and human activity on wind erosion dynamics; (3) to enhance national ecological security shelter through the improvement of the soil conservation component of ecosystem servicing; and (4) to provide a comprehensive and scientific basis for management and planning for the improvement of the ecological environment.

2. Methods and materials

2.1. Study area

Inner Mongolia, the northern frontier province of China (97–126°E, 37–53°N), covers an area of 1.18 million km². As part of the Mongolian Plateau, its average altitude is well over 1000 m a.s.l. It has four major deserts (Badain Jaran, Kubuqi, Ulanbuh and Tengger) and four major sandlands (Hunshadake, Mu Us, Horqin and Hulunbeir). Within a temperate continental climate overall, the climate varies from semi-humid in the east to arid and semi-arid in the west. Climate records from 1990 to 2015 indicate mean annual temperatures from 3 to 6 °C that decrease progressively from south to north. Annual precipitation declines in a gradient from northeast to southwest with a range of 50 to 550 mm, 75% of which occurs from July to September. Strong winds occur frequently in winter and spring. The annual average wind speed is approximately 2.7–3.1 m/s, and maximum wind speed can reach 17 m/s. Sand and dust storms occur on about 5 to 20 days each year in most areas of the province. It has a variety of soil types, including chestnut, aeolian sandy, gray-brown desert, and brown soils, and most are vulnerable to wind erosion. Following the gradients of climate and soil, in 2015 land use/cover types varied from forest, to grassland to unused land, each respectively covering 15.32%, 40.9%, and 30.65% of the total area (Fig. 1). Cultivated land and built-up areas occurred in scattered locations respectively covering 10.54% and 1.35% of the province's area. Water bodies covered only 1.24% of the total area and occurred mainly in the northeast of the province.

Inner Mongolia is an important production base of animal husbandry and domestic livestock grazing is the province's major agricultural activity. This has involved strong human interference in the province for centuries (Zhou et al., 2018). Domestic livestock types are mainly horses, cattle, sheep, camels and goats. Based on agricultural economy types, Inner Mongolia is officially classified into 33 grazing and 21 semi-grazing zones, which together occupy 95.4% of the total area of the province's grasslands. Driven by economic interests closely associated with excessive consumption of grassland resources, grassland degradation is very serious (Zhai et al., 2017). Approximately 46.7 × 10⁴ km², or 74% of the useable natural grassland of Inner Mongolia has been degraded to some extent (Brown et al., 2008). In recent years, in order to relieve grazing pressure and to enhance

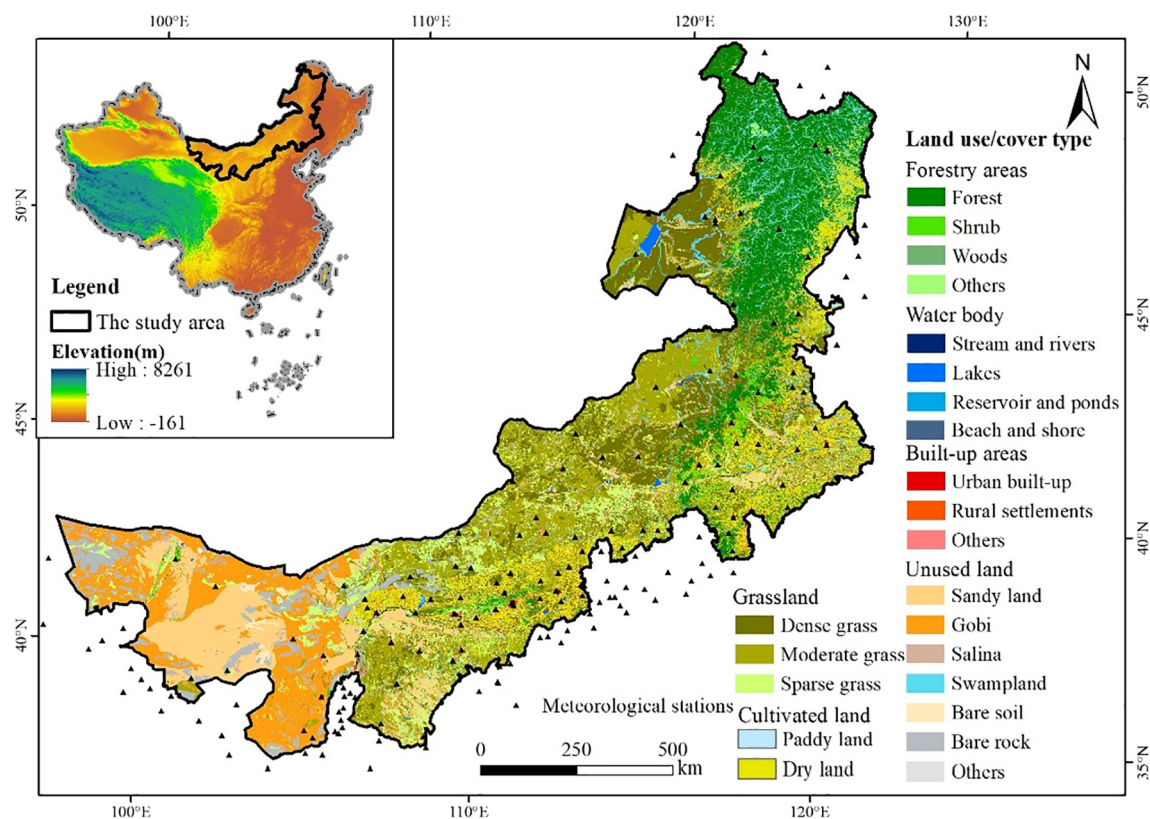


Fig. 1. Geographical location and land use/cover map of Inner Mongolia in 2015.

ecosystem services, nationwide ecological restoration programs have been implemented in Inner Mongolia (Zhang et al., 2018).

2.2. Data preparation and preprocessing

Meteorological data were obtained from 182 meteorological stations in and close to Inner Mongolia that were available from the China Meteorological Data Service Center (CMDC) (<http://data.cma.cn/>) and local meteorological stations. The climate datasets mainly included temperature, precipitation, relative humidity, wind speed, wind direction, solar radiation and sunlight hours data from 1990 to 2015 (Table 1). We interpolated climate data by putting the Digital Elevation Model (DEM) data as a covariate by using ANUSPLIN version 4.2. The DEM data used were the 90 m SRTM (SRTM3 V4.1) (Shuttle Radar Topography Mission) images (<http://srtm.csi.cgiar.org/>) (Table 1). To be congruent with the spatial resolution of remote sensing data, grid cells were resampled into 1 km × 1 km resolution. In our study, the meteorological data derived from these daily, monthly and annual recordings were used to perform a correlation analysis and to run models as input parameters. Based on the Time Series of Strong Sand-Dust Storms in China and the Supporting Dataset from CMDC, variation characteristics of sand-dust storms were analyzed by station-hours as units (Wang et al., 2009).

Table 1

Data required for the RWEQ model assessment of wind erosion. Note: N/A means not applicable.

Data types	Temporal resolution	Spatial resolution	Format
Meteorological data	Daily	N/A	Text
Normalized difference vegetation index (NDVI) dataset	Half-month	1 km	Raster
Land use/cover data	5-year	30 m	Raster
Soil data	N/A	1 km	Raster
Digital Elevation Model (DEM) data	N/A	90 m	Raster

According to the start and end times of sand-dust storms at each meteorological station in and around Inner Mongolia (Fig. 1), station-hours were calculated by duration (in hours). The long-term snow depth dataset was from the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (<http://westdc.westgis.ac.cn>).

Satellite-based NDVI products were obtained from 8 km and 15-day composite GIMMS3g data for 1990 to 2013 (<https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0/>), and the 1 km and 16-day composite MODIS dataset (MOD13A2) (<https://modis.gsfc.nasa.gov/>) for 2000 to 2015 (Table 1). Both of the NDVI datasets have been processed for format conversion, calibration, projection transformation, view geometry, radiation and image mosaics. MODIS-NDVI data were corrected by the MODIS Reprojection Tool (MRT) and the Savitzky-Golay filter. As these two databases were derived from different satellite sensors their spectral ranges and spatial resolutions were different. To reduce errors, we used MOD13A2 data to interpolate and to downscale GIMMS3g data by the linear regression equation of repeating parts between 2000 and 2013. Then we obtained the NDVI datasets with 1 km spatial resolution and for every half-month for 1990 to 2015. Further, we used the Maximum Value Composites (MVC) method to ultimately get the annual NDVI data for 1990 to 2015 and to calculate Fractional Vegetation Coverage (FVC). FVC was calculated from the NDVI image dataset using the dimidiate pixel model method (Liu et al., 2013). Values of pure pixels of bare soil and vegetation mainly depended on 95% confidence of NDVI pixel statistic values.

Land use/cover data with 1 km grids and 5-year intervals from 1990 to 2015, were used to analyze spatiotemporal dynamics (Fig. 1). They were derived from the 1:100,000-scale national China Land Use/Cover Datasets (CLUDs) generated by the Chinese Academy of Sciences (Liu et al., 2014; Liu et al., 2005; Liu et al., 2016) (Table 1). CLUDs were interpreted from medium and high-resolution remote sensing images (Landsat TM/ETM+/OLI and HJ-1A/1B) by the human-computer interactive interpretation method (Kuang et al., 2016). They were divided

into six classes (cropland, forest, grassland, water body, built-up area, and unused land) and 25 sub-classes (Liu et al., 2005; Zhang et al., 2014). Their accuracy was assessed by different professionals and by field verification, with the accuracies of the six classes and 25 subclasses being above 94.3% and 91.2%, respectively (Liu et al., 2014). CLUDs have a national high resolution and provide a long-term sequence for continuously monitoring land use/cover changes (LUCC). Based on the research achievement of the China ecosystem classification system (Ouyang et al., 2015; Shao et al., 2016), this paper merged CLUD classes, separated bare soil and bare rock from unused land into bare land, merged swampland from unused land and water body into wetland/water areas, and other types of unused land into desert ecosystem. This re-classification was composed of seven different ecosystems: farmland, forest, grassland, wetland/water areas, settlement, desert and bare land.

Soil data were provided by the Environmental and Ecological Science Data Center for West China (<http://westdc.westgis.ac.cn>) calculated by the 1:1 million soil data and the Data Sharing Infrastructure of Earth System Science (<http://www.geodata.cn>) to compute the soil erodible fraction EF and the soil crust factor SCF of the RWEQ (Table 1). These datasets included soil sand silt and clay content, organic content, and calcium carbonate content.

Livestock numbers and human population in each county of Inner Mongolia from 1990 to 2015 came from the National Bureau of Statistics (<http://www.stats.gov.cn/>). Small livestock (sheep and goats) were regarded as equivalent to standardized sheep units (SUs), and large animals (horses, cattle and camels) were regarded as five SUs (Su et al., 2003).

2.3. Wind erosion evaluation by the RWEQ model

The RWEQ model was used to predict the wind erosion modulus (defined as soil loss per unit area, Fryrear et al., 1998) for Inner Mongolia from 1990 to 2015. It is an empirical-based model developed by the United States Department of Agriculture (USDA) to estimate soil loss from agricultural fields at a height of 2 m (Fryrear et al., 1998). The RWEQ model was developed for a large geographical scale and the long-term sequence to estimate the sediment transport capacity by wind (Du et al., 2016; Jiang et al., 2016a). In full consideration of factors including climate, soil erodibility, soil crust, surface roughness and vegetation, the RWEQ model estimated the wind erosion modulus by GIS technologies based on ArcGIS platform support and Python programming language. We considered water body, bare land that contains bare soil and bare rock, and alpine valley regions where relief amplitude above 30 m/km as non-wind erosion areas based on the land use/cover types, DEM data and mechanics of wind erosion. The RWEQ involved basic equations as follows:

$$SL = Q_{\max} \left[1 - e^{\left(\frac{x}{S}\right)^2} \right] \quad (1)$$

$$Q_{\max} = 109.8(WF \times EF \times K' \times SCF \times COG) \quad (2)$$

$$S = 105.71(WF \times EF \times K' \times SCF \times COG) \quad (3)$$

where SL is the amount of soil transported by wind at a downwind distance of x (t/kg/a); $Q_{\max}$ is the maximum transport capacity (kg/m); x is the distance from the upwind distance from the maximum wind erosion (m); S is the critical field length at which 63% of maximum transport capacity occurs; WF is the climatic factor (kg/m); EF is the soil erodibility factor (%); K' is the surface roughness; SCF is the soil crust factor; COG is the combined vegetation factor.

The weather factor (WF) reflects the combined effect of all of the meteorological factors on the wind erosion, and is expressed as follows:

$$WF = W_f \times \frac{\rho}{g} \times SW \times SD \quad (4)$$

$$W_f = \frac{\sum_{i=1}^N U_2(U_2 - U_t)^2 \times N_d}{N} \quad (5)$$

$$\rho = 348.0 \left(\frac{1.013 - 0.1183EL + 0.0048EL^2}{T} \right) \quad (6)$$

$$SW = \frac{ET_p - (R + I) \frac{R_d}{N_d}}{ET_p} \quad (7)$$

$$ET_p = 0.0162 \left(\frac{SR}{58.5} \right) (DT + 17.8) \quad (8)$$

$$SD = 1 - P(\text{snow cover} > 25.4\text{mm}) \quad (9)$$

where W_f is the wind factor (m^3/s^3); ρ is air density (kg/m^3); g is acceleration due to gravity (m/s^2); SW is the soil wetness factor; SD is the snow cover factor; U_2 is the wind speed at a height of 2 m (m/s); U_t is the threshold wind speed at a height of 2 m (m/s); N_d is the number of days in the period (usually 15 to 16 days); N is the number of wind speed observations; ET_p is potential relative evapotranspiration (mm); EL is site elevation (km) obtained from DEM data; T is absolute temperature (degrees Kelvin); $R + I$ is rainfall plus irrigation (mm); R_d is the number of rainfall and/or irrigation days; SR is solar radiation (cal/cm^2); DT is average temperature ($^{\circ}\text{C}$); P is probability of snow depth > 25.4 mm.

The soil erodible fraction (EF) and the soil crust factor (SCF) depend on soil texture, silt and clay content and organic-matter content and are defined by the following equations (Fryrear et al., 1994; Zobeck, 1991):

$$EF = \frac{29.09 + 0.31Sa + 0.17Si + 0.33Sa/Cl - 2.59OM - 0.95CaCO_3}{100} \quad (10)$$

$$SCF = \frac{1}{1 + 0.0066Cl^2 + 0.021OM^2} \quad (11)$$

where Sa is the sand content (%); Si is the silt content (%); Sa/Cl is sand to clay ratio; OM is the organic matter content (%); $CaCO_3$ is the calcium carbonate content (%).

The combined vegetation factor (COG) includes three factors: flat residues SLR_f , standing residues SLR_s , and growing vegetation SLR_c , and was calculated by the fractional vegetation cover depending on the effect of withered vegetation and growing vegetation on wind erosion (Gong et al., 2014). The growing vegetation cover was derived from remote sensing data.

$$SLR_f = e^{-0.0438(SC)} \quad (12)$$

$$SLR_s = e^{-0.0344(SA^{0.6413})} \quad (13)$$

$$SLR_c = e^{-5.614(CC^{0.7366})} \quad (14)$$

where SC is soil surface covered with flat residues (%); SA is the silhouette area computed by multiplying the number of standing stalks in 1 m^2 times average diameter (cm) times stalk height (cm); CC is the growing vegetation cover.

2.4. The relative contributions of climate change and human activity to wind erosion

The RWEQ model was used to simulate soil loss by wind erosion (SL_A), which was the natural estimate of existing wind erosion that was influenced by both climate change and human activity. The human-induced soil loss by wind erosion (SL_H) was calculated by the model variable control method that inputs the average climate conditions instead of the actual weather factor (WF). Thus, the climate-induced wind erosion (SL_C) that was only affected by climate change can be simulated in corresponding timescales in every pixel as follows:

$$SL_C = SL_A - SL_H \quad (15)$$

To identify the relative influence of climate change and human activity on SL_A dynamics in every pixel, the absolute slope values of the SL_C and SL_H in the same period were compared for defining the causes of SL_A change. Based on the temporal dynamics of annual wind erosion modulus over the 26-year study period, we used the threshold segmentation method to separate regions where annual wind erosion modulus change was mainly influenced by either climate change or human activity (Tian et al., 2015). Table 2 shows the five different categories of conditions that lead to SL_A change.

2.5. Change trend

The linear slopes of analytical factors (wind erosion, FVC and climatic factors) over time can reflect changing trends and geographical differences more logically and precisely (Ma and Frank, 2006). The slope of the linear time trend was calculated for a certain period and for each pixel by ArcGIS. The formula is as follows:

$$Slope = \frac{n \times \sum_{i=1}^n i \times X_i - (\sum_{i=1}^n i) (\sum_{i=1}^n X_i)}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (16)$$

where i is 1 for the first year, such as 1990, 2 for the next year, such as 1991, and etc.; n is the total number of years of the study period, e.g., 26; X_i is the value of analytical factors for year i . Negative values of the slope represent occurrence of decrease and positive values of slope indicate an overall increase trend. The significance test of slope used t -test and the significance level represents the level of credibility. According to the test results, change trends were divided into the following 5 levels: very significant decrease ($Slope < 0, P < 0.01$), significant decrease ($Slope < 0, 0.01 \leq P < 0.05$), no significant change ($P \geq 0.05$), significant increase ($Slope > 0, 0.01 \leq P < 0.05$), very significant increase ($Slope > 0, P < 0.01$).

Table 2

The relative contribution of climate change and human activity to wind erosion. Note: sSL_A , sSL_C , and sSL_H were the absolute slope values for the SL_A , SL_C , SL_H change trends, respectively.

Hypotheses	Reasons for wind erosion change
$sSL_A \approx 0$ or $P \geq 0.05$	Wind erosion has no significant change (NSC)
$sSL_A > 0$ and $sSL_C < sSL_H$ and $P < 0.05$	Significantly increased wind erosion due to climate change (SISLCC)
$sSL_A > 0$ and $sSL_C > sSL_H$ and $P < 0.05$	Significantly increased wind erosion due to human activity (SISLHA)
$sSL_A < 0$ and $sSL_C > sSL_H$ and $P < 0.05$	Significantly decreased wind erosion due to climate change (SDSLCC)
$sSL_A < 0$ and $sSL_C < sSL_H$ and $P < 0.05$	Significantly decreased wind erosion due to human activity (SDSLHA)

3. Results

3.1. Model calibration and accuracy assessment

The RWEQ model was originally developed for estimating soil loss of arable land in the USA. According to the input files, we adjusted several of the parameters to their value ranges. To localize key model parameters and to verify the results of model simulations, we obtained hundreds of field survey and data sampling observations for plant compositional structure, withered vegetation coverage, soil properties, and indoor and field wind tunnel experiments from 2004 to 2013. The RWEQ model requires the wind speed at the height of 2 m, however, the daily wind data from meteorological stations was from anemometers at the height of 10 m. Therefore, according to the achieved result, some transformation was undertaken (Elliot, 1979). The classification criteria for soil texture in China is the same as the international criteria, but for soil textural criteria used for calculating EF , SCF and K' , the American criteria were used. Therefore, soil particle contents were converted from the international criteria to the American criteria using the Logistic growth model proposed by Skaggs et al. (2001).

During field observations, the withered vegetation covers of different ecosystems were first obtained by combining digital photography and traditional visual estimation methods (Fig. 2 a, b). Then, we calculated the regression relationship of withered vegetation cover with FVC calculated from remote sensing data. K' was measured using a roller chain method and the actually measured sand and grassland roughness factors provided values of 0.96 and 0.69 respectively (Gong, 2014) (Fig. 2 c, d). We mainly used the ^{137}Cs tracing technique to investigate the wind erosion modulus of the RWEQ model in Inner Mongolia (Chi, 2015). Soil stratification was divided into 0–2–4–6–8–12–18–24 cm to make sampling intervals (Fig. 2 e). Soil samples were dried, crushed, weighed, and packaged in preparation for analysis. (Fig. 2 f). We compared the measured data from observation plots with the simulation results from the RWEQ model for pixel values. After testing for the accuracy of the simulated values (Fig. 2 g), we found that the simulation values were significantly correlated with the measured values ($P < 0.001$). Further, results of the RWEQ model were compared with those from previous studies (Gong et al. (2014), Chi (2015), Du et al. (2016), Guo (2012), etc.) that were similar to ours.

3.2. Temporal-spatial changes of wind erosion

Between 1990 and 2015, the distribution of average annual wind erosion modulus in Inner Mongolia gradually decreased from northeast to southwest (Fig. 3 a). This distribution was strongly correlated with the regional spatial distribution of weather conditions and vegetation cover. According to the standard for “Classification criteria for soil-erosion intensities” (SL190–2007) (Ministry of Water Resources of the People's Republic of China, 2007), the wind erosion intensity in Inner Mongolia was categorized by six grades (Fig. 3 a). (1) Areas of slight erosion intensity (200–2500 t/km²/a) that were predominately in the grassland and forest areas of eastern and central Inner Mongolia (50.34% of the area); (2) areas with tolerable erosion intensity (<200 t/km²/a) that occurred mainly in forest areas of eastern Inner Mongolia (14.03% of the area); (3) regions with moderate erosion intensity (2500–5000 t/km²/a) that occurred mainly in grassland of western Inner Mongolia (12.46% of the area). The percentages of areas with (4) severe (5000–8000 t/km²/a), (5) very severe (8000–15,000 t/km²/a), and (6) destructive (>15,000 t/km²/a) erosion intensities were 8.73%, 7.55% and 6.91% respectively. These areas with severe erosion were mainly in the large deserts, sandy lands, and sparse grasslands of southwestern Inner Mongolia with soil types mainly belonging to aeolian sandy soil and brown soil with high soil erodibility.

The changing trends of annual wind erosion modulus during 1990 to 2015 are shown in Fig. 3 b. About 43.66% of wind eroded areas showed no significant changes. Areas with decreased wind erosion

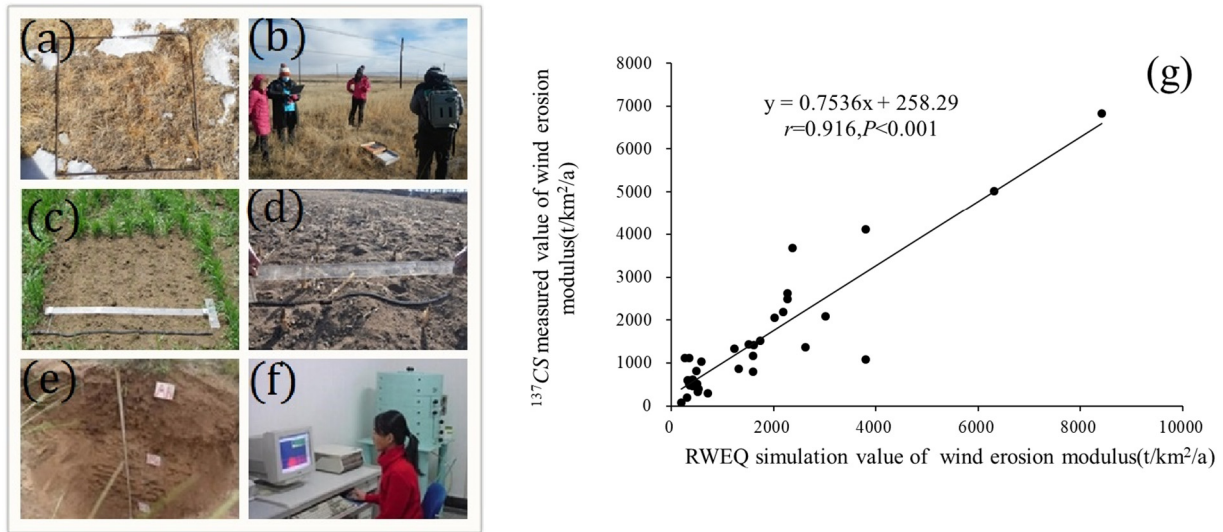


Fig. 2. Photographs of (a, b) measurement of withered vegetation coverage, (c, d) soil roughness, (e) stratified soil sampling, (f) ^{137}Cs test and (g) calibration accuracy test of wind erosion modulus.

predominated throughout the study area, occupying 49.23% of the area. Areas with significant increase accounted for only 7.11% of the study area and these were mainly distributed in the region around the Hulunbeir sandland and in the middle of Inner Mongolia. Compared with the situation in 1990, areas with destructive erosion intensity decreased most by 5.2%; areas with slight and moderate erosion intensities decreased by 4.01% and 4.85% respectively; areas with tolerable erosion intensity increased by 13.2%; while other erosion intensities did not

show a clear change. These changes indicated that the wind erosion risk of the study area had become less during the 26-year period.

From 1990 to 2015, the mean annual value of the wind erosion modulus was $3558.18 \text{ t}/\text{km}^2$, with the lowest value $2309.53 \text{ t}/\text{km}^2$ occurring in 2005 and the highest value $5361.95 \text{ t}/\text{km}^2$ in 2001. For the entire study area, the wind erosion modulus, while showing marked annual fluctuations, significantly decreased over the 26 years with the slope of $-52.32 \text{ t}/\text{km}^2/\text{a}$ ($r = -0.532, P < 0.01$) (Fig. 3 c). The wind erosion

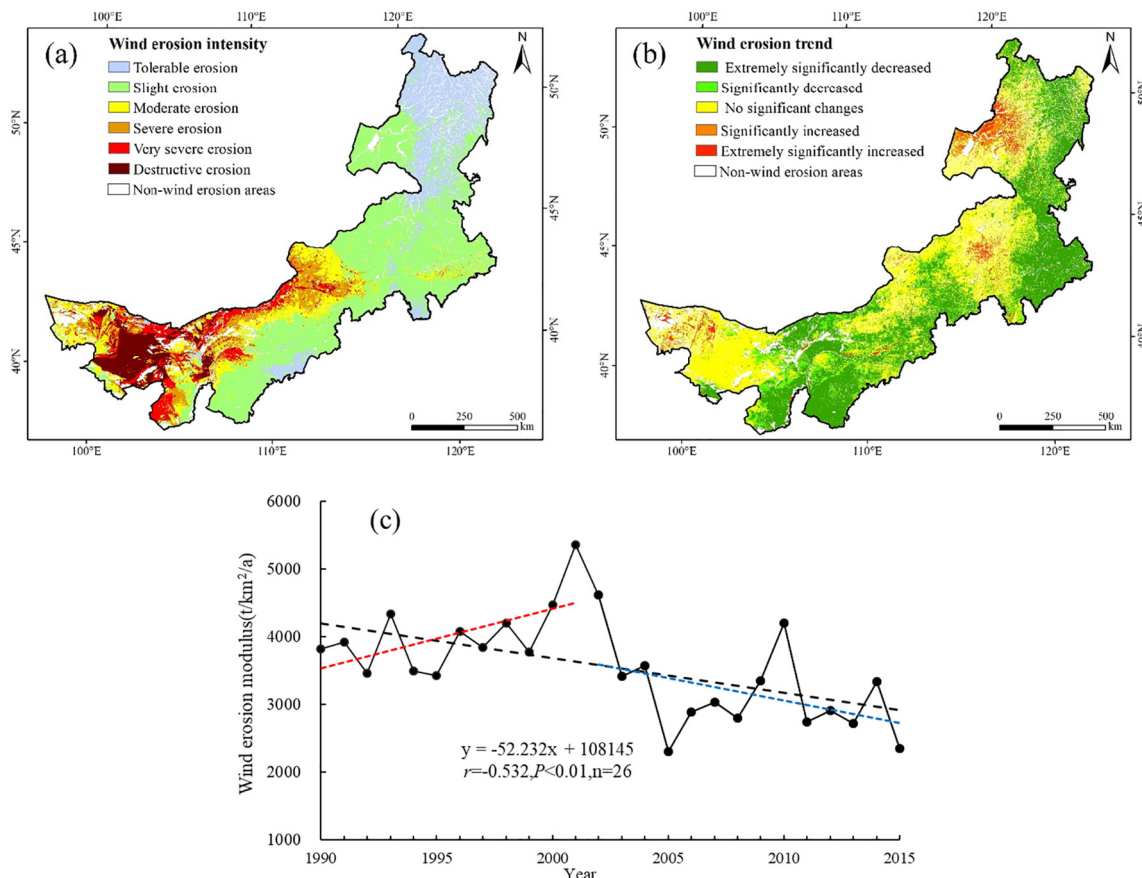


Fig. 3. Distribution maps and spatial differences of wind erosion in Inner Mongolia, (a) the average intensity during 1990 to 2015, (b) the change trend and (c) inter-annual variations from 1990 to 2015.

modulus showed different trends of changes in the 1990 to 2001 and 2002 to 2015 periods. From 1990 to 2001, the wind erosion modulus increased at a rate of 87.49 t/km²/a, with a significant total increase of 40.37% ($P < 0.05$). In the period 2002 to 2015, the wind erosion modulus decreased at a rate of −67.03 t/km²/a, with a decrease of −49.12%.

3.3. Changes in wind erosion of different terrestrial ecosystems

During 1990 to 2015, wind erosion of the four main ecosystem types markedly decreased (Table 3). The desert ecosystem had the greatest wind erosion but showed the largest decrease of wind erosion during the period. The grassland ecosystem had a high risk of wind erosion because of its low vegetation cover and erodible soils with higher sand content. However, compared to desert, the cover provided by grassland species played an important role in sand fixation. Due to higher vegetation cover that increased the threshold wind speed, the forest ecosystem had the lowest wind erosion and showed the smallest change. The farmland ecosystem had lower wind-erosion than grassland and also a greater slope of reduction of erosion during the study period.

3.4. Relative roles of climate change and human activity in wind erosion

To identify the causes of wind erosion dynamics over the 26 years, we compared the absolute values of the slopes of the climate-driven and human-induced wind erosion for each pixel (Fig. 4). Since the processes of wind erosion were very complex and involved many factors, in this section, we consider the distribution of driving forces for wind erosion dynamics in Inner Mongolia that were attributable to either climate change or human activity. For regions with significantly decreased wind erosion, 40.72% was caused by climate change, and 8.51% was caused by human activity. For regions with significantly increased wind erosion, 4.29% was caused by climate change, and 2.82% was attributable to human activity.

4. Discussion

4.1. The relationship between fractional vegetation cover changes and erosion

Vegetation dynamics determined by the interaction of climate change and human activity is an important ecological process in wind erosion. Fractional vegetation cover (FVC), by serving as a quantitative indicator of environmental changes, can comprehensively reflect vegetation dynamics (Ivits et al., 2013). FVC have long been proposed to be the key assessment indicator of soil and water conservation function. It can effectively protect surface soil by moderating wind speed and by decreasing sediment discharge (Shen et al., 2016). Increased vegetation cover can effectively fix and reduce the amount of wind-blown dust to control wind erosion (Xing et al., 2015; Zhao et al., 2017). We observed that for 1990 to 2015, the average FVC of Inner Mongolia showed a clear increasing trend (Fig. 5 a, c). For the same period wind erosion had a remarkable decline (Fig. 3 c). Increased FVC, which led to reduction of the erodibility of soil and increased soil roughness, significantly reduced wind erosion risk. Spatially, FVC had an obvious decreasing trend from northeast to southwest, whereas wind erosion had the opposite

ascending trend (Fig. 3 a, 5 b). Furthermore, FVC in the southwest corner and in the northeast region declined as wind erosion of these regions increased.

For the correlation coefficient between wind erosion and FVC, there was an overall significant negative correlation accounting for 40% of the total area ($r = 0.62$, $P < 0.01$, Fig. 5 d). Areas with serious wind erosion mainly occurred in areas with low FVC. In particular, the annual average FVC in the southwest region was below 20% from 1990 to 2015, and these areas suffered destructive wind erosion. FVC in the northeast was higher so wind erosion was correspondingly lower.

Ecosystems with different FVCs had different levels of wind erosion. Annual average FVC of grasslands was 23% and improved the most for the ecosystems from 1990 to 2015. Grasslands were able to improve soil physical characteristics and to consolidate sand to effectively reduce wind erosion. Increased grassland FVC enhanced the ecological function of windbreak, which consequently increased sand fixation. Forest lands, with annual average FVC of 53% also had strong windbreak and sand fixation capacity (Table 3, Fig. 5). Desert, with low average FVC (12.58%), had the largest proportion of wind erosion (66%).

4.2. Effect of climate change on wind erosion

Climate change was the dominant controlling factor of wind erosion dynamics, mainly through its effects on wind speed, precipitation and temperature (Du et al., 2017; Toy et al., 2002; Zhao et al., 2017). Of these effects, wind is the main determining climatic driving force causing wind erosion, and wind speed is the main factor in sediment transport (Shao, 2000). Further, sand-dust storms happen when strong wind blows dust off the ground, vitiates the air, restricts horizontal visibility to <1 km and strongly affects wind erosion intensity (Administration., 2005).

We selected mean annual wind speed and station-hours of sand-dust storms as the indicators of wind changes on wind erosion. During 1990 to 2015, mean annual wind speed of Inner Mongolia had a significant decreasing trend with a slope of −0.006 m/s/a ($P < 0.001$) (Fig. 6 a). When wind speed significantly decreased, wind erosion decreased. The spatial distribution characteristics of wind erosion were similar to those of wind speed. With higher average wind speed, especially in arid regions with low rainfall and low vegetation cover, wind erosion was more serious. There was a significant positive linear correlation between the annual wind erosion modulus and mean annual wind speed ($r = 0.73$) (Fig. 6 b). Areas with significant or highly significant correlation of wind speed and wind erosion occupied 84.4% of Inner Mongolia. This indicates that wind speed had a strong impact on the spatial distribution and temporal variation of wind erosion. In addition, station-hours of sand-dust storms calculated for the period 1990 to 2007 were also positively and very significantly correlated with the wind erosion ($r = 0.54$, $P < 0.05$). Further, the peak values of station-hours of sand-dust storms and the annual wind erosion modulus synchronously occurred in the same years of 2001 and 2006, respectively (Fig. 6 a, 3c). This may explain why sand-dust storms affected the peak values of the wind erosion modulus by lowering surface roughness, reducing soil cohesion and decreasing soil moisture, which together leads to the intensification of wind erosion.

Precipitation and temperature not only directly affected soil moisture and adhesion but also modulated wind erosion by vegetation (Neuman, 2003). Although annual precipitation and mean annual temperature did not change significantly (Fig. 6 c), we found that in particular areas they were significantly correlated with wind erosion.

For the relationship between wind erosion and precipitation (Fig. 6 d), significant negative correlation between them occurred mainly in sandy and desert areas of western and central Inner Mongolia. The most serious wind erosion processes usually occurred in these arid and semi-arid areas. Although areas with annual precipitation <400 mm to as low as 200 mm and with FVC below 20% were prone to wind erosion, increased precipitation in these areas stimulated

Table 3
Wind erosion rates of four terrestrial ecosystems in Inner Mongolia from 1990 to 2005.

Ecosystem types	Wind erosion			
	Mean (t/km ² /a)	Amount (million t/a)	Slope (t/km ² /a)	CV (%)
Desert	10,195.93	2574.53	−110.35	1.11
Grassland	2420.68	1134.35	−36.74	1.23
Forest	296.28	52.00	−12.27	1.44
Farmland	1130.58	136.48	−60.64	1.23

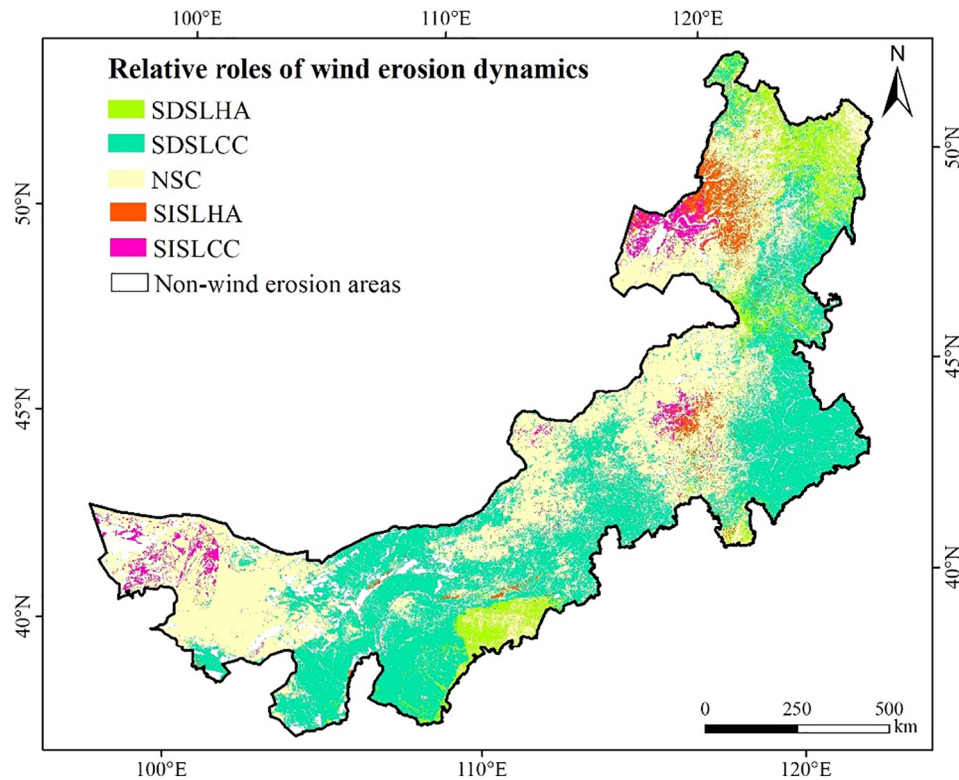


Fig. 4. Spatial distribution of different causes of wind erosion in Inner Mongolia from 1990 to 2015. Categories: NSC: Wind erosion had no significant change; SISLCC: significantly increased wind erosion due to climate change; SISLHA: significantly increased wind erosion due to human activity; SDSLCC: significantly decreased wind erosion due to climate change; SDSLHA: significantly decreased wind erosion due to human activity.

plant growth, increased FVC, and subsequently improved the level of protection against wind erosion (Fig. 5 c, 6 c). By contrast, wind erosion in some areas, e.g. Hulunbeir sandland and Horqin sandland (Fig. 1), decreased further as precipitation decreased (Fig. 3 b, 6 d). The likely reason for this is that as the meteorological conditions in these areas became warmer and drier (Fig. 6 c, e), their FVC decreased (Fig. 5 c) and further grassland degradation and desertification was aggravated by wind erosion. For most parts of eastern and southern Inner Mongolia, no significant relationships were found between wind erosion and annual precipitation. This could indicate that annual precipitation in these areas was not the primary essential factor determining wind erosion. Variation of precipitation was more likely to indirectly influence wind erosion by affecting vegetation growth (Fig. 5).

As temperatures rose, especially in the area surrounding the Badain Jaran desert (Fig. 1), evaporation of surface water increased (Fig. 6 e, f). This made the soil surface drier and more vulnerable to wind erosion. Especially where surface temperatures of deserts and sandy lands rose faster than that of surrounding areas, cold air invaded and made convection stronger and sand-dust storms occurred more readily. Conversely, the decrease in temperature in parts of Inner Mongolia reduced water evaporation, causing a reduction in the wind erosion. However, temperature had significant negative correlation with wind erosion in certain areas. In middle and eastern regions of Inner Mongolia where mean annual temperature was generally lower than that in western regions, the increase in temperature promoted vegetation growth and enhanced sand-fixation ability and reduced wind erosion.

4.3. Effect of human activity on wind erosion

Human activity had a much smaller effect (11.33% of the total area) on wind erosion dynamics in Inner Mongolia compared with that of climate change (45.01% of the total area). We considered human activity mainly being of three forms: grazing, human-caused LUCC, and implementation of ecological restoration programs.

4.3.1. Effect of grazing on wind erosion

To meet needs for survival and development, humans continuously use land and change its form, altering soil moisture, structure and nutrient status thus causing spatial-temporal changes of wind erosion impacts. Grazing by domestic livestock can modify and damage soil surfaces and destroy soil crusts by treading on them. For natural grasslands, grazing is considered the major driver of grassland degradation. When stocking levels exceed the carrying capacity of grassland ecosystems, long-term overgrazing, especially where there is low FVC, can increase the risk of grassland degradation and even cause desertification (Manzano and Návar, 2000). Grassland degeneration may form new sandstorm sources, consequently intensifying wind erosion.

With rapid development of local social-economies, human population and livestock numbers have increased markedly in recent decades. We recorded the total numbers of livestock and assessed their impact on wind erosion. Total livestock numbers at mid-year and at year-end both showed significant increasing trends between 1990 and 2015 at rates of 3.88×10^6 SUs/a ($P < 0.001$) and 1.82×10^6 SUs/a ($P < 0.001$), respectively (Fig. 7). By 2015, the number of livestock at mid-year had reached 175.26 million SUs. As livestock numbers kept growing at an unprecedented rate, the serious consequences of over-stocking causing reduction of FVC and trampling and pulverization of soil intensified.

4.3.2. Effect of LUCC on wind erosion

LUCC usually affects wind erosion by changing soil surface roughness and soil chemical and physical characteristics over a long time scale, and this process is slower compared to climatic factors and grazing (Mahrooz et al., 2016; Zhao et al., 2017). During 1990 to 2015, the area of unused land increased by 12.85% (39.99×10^3 km²) and its wind erosion decreased by 1290.94 million ton. This constituted 77.01% of the decrease of wind erosion for all of Inner Mongolia (Table 4). Also, increase of grassland and forest developed on previously unused lands may assist reduction of wind erosion in Inner Mongolia.

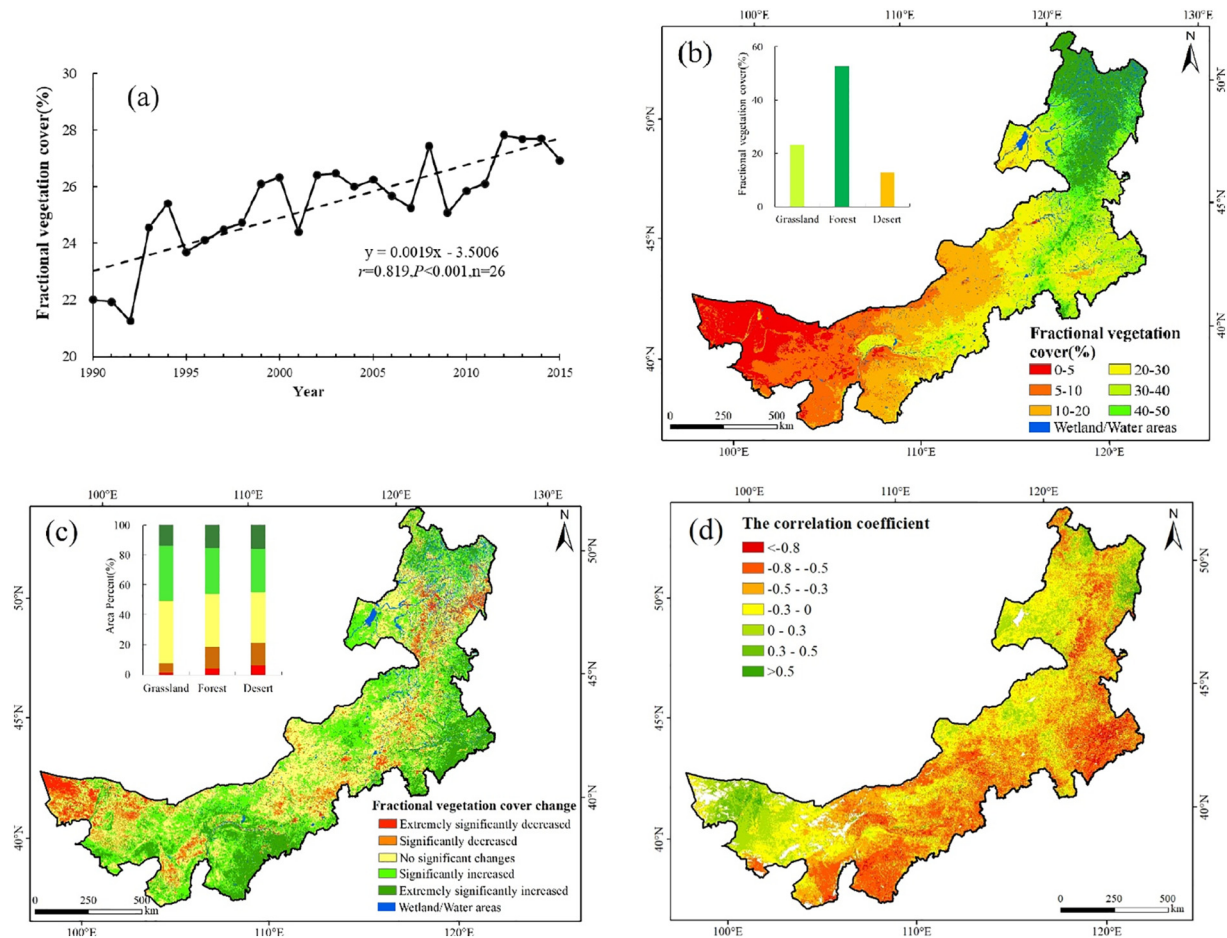


Fig. 5. Changes of fractional vegetation cover (FVC) for Inner Mongolia from 1990 to 2015, (a) temporal change, (b) spatial variation, (c) change direction and (d) correlation coefficients (r) between wind erosion and FVC.

However, more likely LUCC, particularly in areas with severe wind erosion, would increase the susceptibility of soil to wind erosion. Land use for grain production to feed the soaring population and to meet demands for economic development resulted in large losses of grassland and forest and rapid expansion of cultivated land and built-up areas. The human population of Inner Mongolia increased from 21.62 million in 1990 to 25.11 million in 2015, an increase of 16.11% (Fig. 7). From 1990 to 2015, net cultivated land increased by $17.13 \times 10^3 \text{ km}^2$ in the northeast and mid-Inner Mongolia and this was mainly at the expense of grassland ($13.5 \times 10^3 \text{ km}^2$) and forest ($2.79 \times 10^3 \text{ km}^2$). Although the wind erosion modulus of farmlands was lower than that of grasslands (Table 3), the capacity of grassland to fix sand was greater than that of farmlands (Jiang et al., 2016b). Newly cultivated land was mostly distributed in areas with higher temperatures and rainfall. Conversion of grassland and forest to cultivated land not only directly decreased their areas, it also increased their fragility, severely damaging the soil moisture status and structure of the surface soil of these primary ecosystems. Further, these conversions, by involving cultivation, formed widespread bare, sandy and abandoned lands in spring and winter, consequently generating new sand sources. Meanwhile, increase of the area of cultivated land consumed more of the regions water resource for irrigation leading to drying up of the down streams of rivers, lowering of groundwater levels, and reducing the area of water body. These effects of cultivation caused great concern in regard to increase of wind erosion hazards.

Besides, satellite imagery from 2000 to 2010 showed that the area and number of opencast mines increased by 33.23% and 67.88%, respectively. By destroying forest and grassland for mining or discarding slag that burns vegetation, especially in the southwest of Inner Mongolia

(Fig. 8 IV), soil surfaces lost vegetation protection increasing their susceptibility to wind erosion and sand-dust storms.

Marked changes also occurred for unused land and forest. New unused land (largely consisting of sandy land) was mainly derived from grassland in the northeastern Hulunbeir sandland and from the western desert margins (Fig. 8 I). This grassland desertification reduced vegetation coverage and roughness of underlying soil surface, thereby decreasing sand fixation service. Conversion of $21.16 \times 10^3 \text{ km}^2$ of grassland to forest occurred from 1990 to 2015. However, wind erosion of these areas in northeast and mid-Inner Mongolia appeared to increase (Fig. 8 II, III). Grasslands were mostly converted to plantation forest and the sand-fixation ability of plantation forest in the early stage of tree establishment was lower than that of the grasslands they replaced (Jiang et al., 2016b). In addition, the area of water body, which has no wind caused soil erosion, decreased year by year (Table 4), resulting in reduced runoff and increased the risks of wind erosion.

4.3.3. Effect of implementation of ecological restoration programs on wind erosion

In order to combat desertification and control wind erosion, since 2000 the Chinese government has implemented several major nationwide ecological programs to promote sustainable land management in Inner Mongolia. These measures intend to shift provision of ecosystem services from industrial development to the enhancement of sand fixation service. The most important of these programs are the Beijing-Tianjin Wind/Sand Source Control Program (BTWSSCP) begun in 2001, the Grazing Withdrawal Program (GWP) begun in 2003, and the Ecological Subsidy and Award System (ESAS) implemented in 2011 (Shao et al., 2017). Up to the present, there are 31 counties

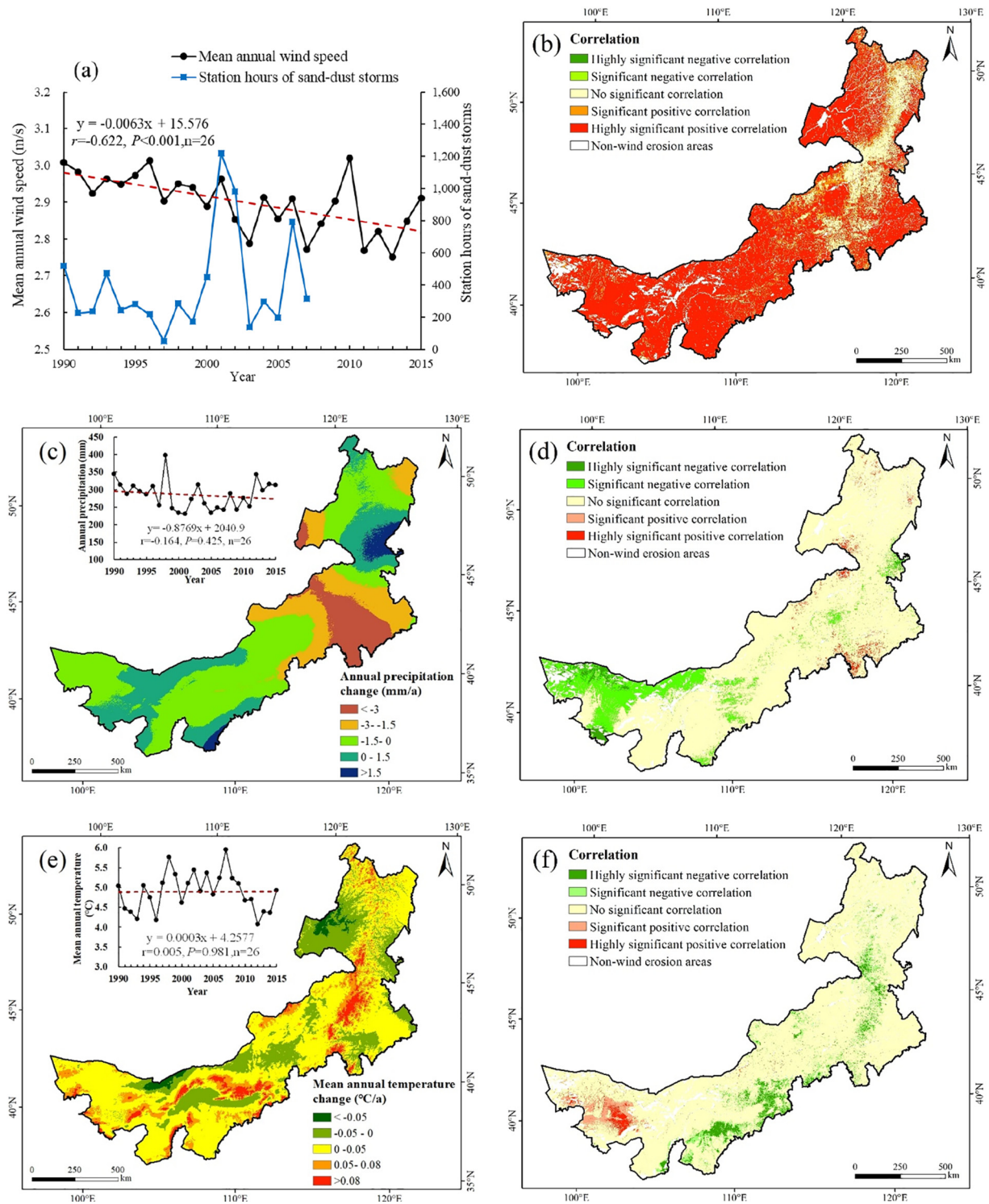


Fig. 6. Relationships between wind erosion and climate factors in Inner Mongolia from 1990 to 2015. (a) Temporal variations of mean annual wind speed and station hours of sand-dust storms, (b) spatial pattern of correlations between wind erosion and wind speed, (c) spatial variation of annual precipitation, (d) spatial pattern of correlations between wind erosion and annual precipitation, (e) spatial variation of mean annual temperature, and (f) spatial pattern of correlations between wind erosion and mean annual temperature.

(districts, banners) applying both GWP and ESAS, 20 counties (districts, banners) applying both BTWSSCP and ESAS, and 16 counties (districts, banners) applying one of these three ecological restoration programs (Chen et al., 2017). These programs have reduced grazing pressure and gained increases of vegetation recovery (Zhou et al., 2018). Although livestock numbers have increased since the implementation of these programs, there was no further increase of erosion for the whole region. Statistics of areas where significant decrease of wind erosion

caused by human activity occurred are shown in Fig. 4. These are mainly areas where ecological restoration programs were implemented. This may be the reason for the wind erosion modulus showing a turning point in 2002.

The BTWSSCP was implemented mainly to reduce the sandstorm harm affecting Beijing and land surrounding the city. From 2002 to 2013, the government invested 5.68 billion RMB in this program to complete ecological reconstruction of 16.81 million ha in Inner

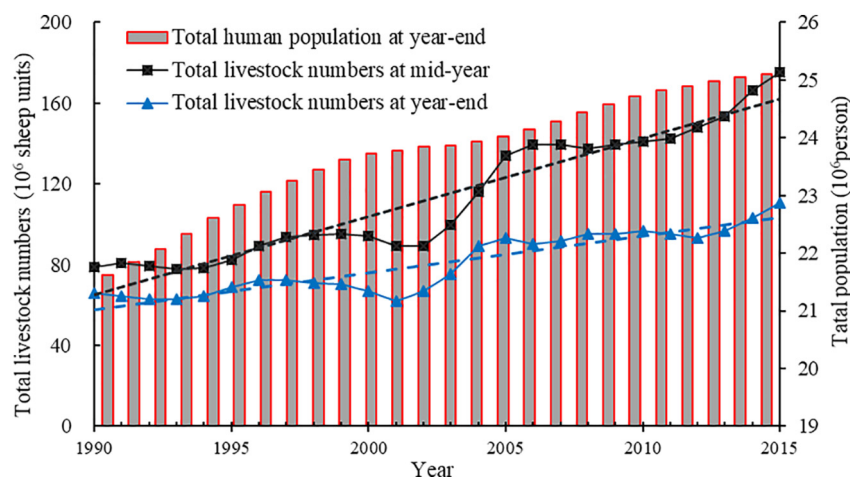


Fig. 7. Temporal variations of total livestock numbers and human population in Inner Mongolia from 1990 to 2015. Note: Dashed lines are regressions across years.

Mongolia. ESAS has been implemented on 67.3 million ha of natural grassland in Inner Mongolia since 2011. By 2015, the area of introduced grass planting and seeding reached 3.5 million ha. Sheds for forage storage were built to serve 8.2 million km², and the proportion of livestock barn feeding increased by 22% (Li and Yao, 2016).

To some extent, the common goals of the ecological restoration programs have been to reduce grazing pressure and increase vegetation cover. The ratio of total livestock numbers at the end of the production year to that in the middle of the livestock production year decreased from 82% in 1990 to 63% in 2015 (Fig. 7). These changes indicate that the marketing rate of fattened stock has risen allowing reduction of stocking rate in winter by increasing the selling rate of livestock in autumn. Ecological measures were also applied to reduce grassland degeneration by improving vegetation cover and increasing vegetation-covered areas. Landscape modifications that either increase or decrease vegetation cover have remarkable effects on sand fixation dynamics. With application of ecological programs, vegetation cover has been significantly increased to reduce wind erosion risk and improve the sand fixation service.

4.4. Remediation strategies to control wind erosion

Our study indicates that the percentage area of wind erosion change caused by climate change dominated the whole study area. Human activity helped to reduce wind erosion in some areas but increased the degree of wind erosion in others. Because Inner Mongolia is characterized by arid and semiarid climates, timely monitoring is required to have accurate information on wind erosion risks. Biological measures, engineering measures, and land use planning, are either applied separately or integrated together to decrease or prevent wind erosion. Use of remote sensing, meteorological, and field observation data will enhance ecological monitoring to determine the changing status of wind erosion over time in different locations. Regular monitoring of land degradation changes is needed to assist control of wind erosion. Step-by-step

measures are required to assess local conditions in order to reduce their susceptibility to wind erosion, and this especially applies to desert areas with very low FVC. For desert ecosystem, establishment of shrubs to function as windbreaks combined with grasses to provide a protective barrier against wind erosion, is required. In order to reduce the wind erosion risk to grasslands recommended steps are to (1) minimize the grazing impact on natural grassland, especially in spring, to promote growth of native grasses; and (2) increase supplementary feeding or reduce livestock numbers to alleviate livestock grazing pressure on grasslands and to ensure development of animal husbandry is sustainable. For forest ecosystems, establishment of windbreaks to reduce wind speed and to provide ground cover is required to hold soil. For farmlands, effective practices to reduce wind erosion are no-tillage in spring and winter and increasing the amount of crop stubble left after grain harvesting.

While wind erosion in Inner Mongolia has been eased and controlled to a certain degree, areas with particularly fragile ecological environments have not radically changed or have become more prone to wind erosion. Wind erosion intensities in parts of Inner Mongolia are still increasing and 23.19% of the total area still has severe erosion intensity. Continued promotion of key ecological programs and their separate administration in different parts of Inner Mongolia are still required to speed the process of vegetation recovery and improvement of the province's ecosystems.

5. Conclusions

In this study, using the RWEQ model, we assessed the spatial and temporal dynamics of soil erosion by wind in Inner Mongolia for the period 1990 to 2015. Furthermore, we discriminated and quantified the relative effects of climate change and human activity on the wind erosion to identify driving forces. The results show that areas of slight erosion intensity dominated in Inner Mongolia by occupying 50.34% of the area. The wind erosion modulus in Inner Mongolia had a declining trend

Table 4

Land use/cover changes in Inner Mongolia from 1990 to 2015 (area: thousand km², percentage/rate: %, amount: million ton).

Land use/cover types	1990		2015		Land use/cover changes		Wind erosion changes	
	Area	Percentage	Area	Percentage	Area	Change rate	Amount	Contribution rate
Cultivated land	103.6	9.04	120.73	10.54	17.13	16.54	−143.81	8.58%
Forest	167.64	14.63	175.52	15.32	7.88	4.7	−71.01	4.24%
Grassland	538.06	46.96	468.66	40.9	−69.4	−12.9	−137.93	8.23%
Water body	14.49	1.26	14.24	1.24	−0.25	−1.7	−20.15	1.20%
Built-up areas	10.88	0.95	15.52	1.35	4.64	42.62	−12.47	0.74%
Unused land	311.21	27.16	351.21	30.65	39.99	12.85	−1290.94	77.01%

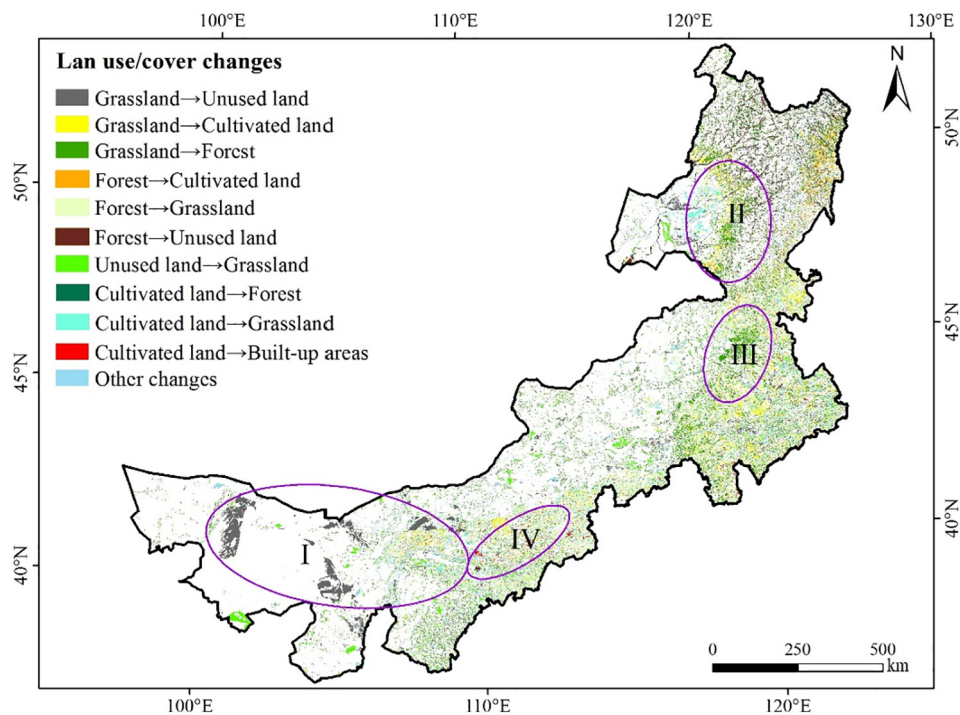


Fig. 8. Main land use cover changes in Inner Mongolia from 1990 to 2015. *Note:* white areas had no changes of land use/cover; I: main area of conversion from grassland to unused land; II, III: main areas of conversion from grassland to forest; IV: main area of conversion from grassland to built-up areas.

with a slope of 52.23 t/km²/a. Furthermore, the wind erosion modulus declined more quickly after it reached its peak of 5361.95 t/km² in 2001. Through analysis of the relationships among wind erosion, climatic factors, and different forms of human activity, we found that climate change was the dominant factor controlling changes of wind erosion over the whole area. The effects of human activity were usually more localized. During the 26 years, change towards warmer, wetter and less windy climate and the implementation of ecological restoration programs have contributed to vegetation recovery and decrease of wind erosion. Observed reduction in wind speed and severity of dust events has generally lessened wind erosion. Ecological restoration programs have played a positive role in decreasing wind erosion by means of reversing the trend of grassland degeneration. However, increase of wind erosion in some regional areas continues and is caused by ongoing overgrazing and other inappropriate land uses.

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